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Simulation and experimental studies on acoustic scattering characteristics of surface targets☆

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A B S T R A C T

Based on the Kirchhoff approximation, a prediction method on the echo characteristics of surface targets was presented, considering the reflection effect of water surface. Specifically, the performance of this proposed approach was evaluated with acoustic scattering by a rigid semi-submerged sphere. A 3D warship model, built upon the fundamentals of the proposed approach, was introduced and validated by the acoustic scattering experiment on lake. The simulation and experimental results show together that the sea surface has a significant influence on the echo characteristics represented as several echo highlights depending on the acoustic path difference. With beam forming technique, the results also reveal that the echo characteristics are mainly from the scattering contribution of stem, midship and rudders. Furthermore, some relevant parameters including length, width, range and speed can be inferred from experimental results. In summary, this work presents a systematic effort to predict the echo characteristics of surface target with new method.

1. Introduction

Acoustic echo of surface warships carrying a great deal of navigational information for accurate positioning and tracing has attracted extensive attention domestic and overseas. The methods on studying acoustic scattering characteristics of surface targets can be classified as: analytical, numerical and approximate methods. As separation of variable is required, the analytical method is only applied for simple-shape targets, such as planar, spherical, cylindrical or ellipsoidal targets. Focus on the analytical method is mainly put on how to compute the special function more accurately and speedily [1–3]. The numerical methods represented by Finite Element Method (FEM) [4,5], Boundary Element Method [6] (BEM) and T-matrix [7–9] are mainly used to predict the acoustic scattering characteristics of small size targets at low frequencies [10,11]. Though a large of efforts have been made to improve the calculation speed, such as hybrid smoothed FEM [12–14] (HS-FEM), multi-domain BEM [15,16] (MBEM), the computation time of these numerical methods is unacceptable in dealing with realistic problems yet. With the frequency increasing, the approximate method represented as Kirchhoff approximation plays a more and more important role. Based on Kirchhoff approximation, rigid or local impedance boundary condition is assumed and the scattered field is regarded as the sum of scattered waves from each element of the targets independently [17]. Fawcett [18] proposed a numerical discretization and transformation into the time domain to model high-frequency pulse scattering from rigid bodies. Wendelboe [19] derived the far field scattered pressure from the plane triangular facets, and Lee [20] calculated the impulse response of the impedance polygon facet. Fan and Tang [21–23] proposed a method called Planar Elements Method (PEM), which has been widely used in modeling acoustic echo of various kinds of complex targets.

Compared with those in free field, simulation and experimental studies on acoustic scattering characteristics of surface targets are much less. Based on PEM and image source principle, Wang [24] gave Target Strength (TS) of several typical fishing vessels in different sizes or tonnages. Wang [25] calculated TS and orientation distribution characteristics of warships at the far field. In this paper, theoretical proof of Kirchhoff approximation on acoustic echo of surface targets was given at first. Acoustic scattering characteristics of surface targets are studied in numerical simulation and scaling experiment. It is organized as follows: In Section 2, we briefly introduced Kirchhoff approximation on acoustic echo of surface targets and verified it to be feasible taking a rigid semi-submerged sphere as an example. In Section 3, we described the modeling method of warship, and presented the calculation process of echo characteristics. Furthermore, we discussed the influence of some parameters including sea surface and range. In Section 4, we

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conducted an acoustic scattering experiment of moving warship model on the lake and analyzed the validity of numerical modeling. Finally, a summary and a discussion of the results are presented in Section 5.

2. Kirchhoff approximation on acoustic scattering of surface targets

The warship is a common surface target, which can be regarded as the shell structure with certain draught. The scattered field is the total contribution of underwater shell and its structure, considering reflection effect of sea surface and seabed. But we can ignore the reflection effect of seabed when the draught is much less than the water depth and the receiving point is close to the target.

As derived in Ref. [26], Kirchhoff approximation on acoustic scattering of surface targets is only briefly introduced here. Compared with these classical forms, PEM based on Kirchhoff approximation has an advantage in calculating the acoustic echo of complex surface targets, and the reflection effect of sea surface is also taken into consideration in this paper.

With time dependence of all quantities assumed as $e^{-j\omega t}$, where ω is the angular frequency and t is time, the scattered field can be expressed as

$$p_s(\vec{r}) = \frac{1}{4\pi}\int_S \left[p_s(\vec{R})\frac{\partial G(\vec{r},\vec{R})}{\partial \vec{n}} - \frac{\partial p_s(\vec{R})}{\partial \vec{n}}G(\vec{r},\vec{R})\right]dS, \tag{1}$$

where $p_s(\vec{r})$ is the scattered pressure at the receiving point with radius vector $\vec{r}$ in the semi-infinite space, $\vec{n}$ is the outward normal vector on the boundary of the target, and $G(\vec{r},\vec{R})$ is the semi-infinite space Greens function

$$G(\vec{r},\vec{R}) = \frac{e^{jkr}}{r} + V(\theta)\frac{e^{jkr_1}}{r_1}, \tag{2}$$

in which $V(\theta)$ is the reflection coefficient of the interface and $r(r_1)$ denotes radius vector between the receiving point and the real (image) points on the boundary of the target. For the rigid or soft interface, V is equal to 1 or -1, respectively.

For rigid targets at high frequencies, it is satisfied on the boundary of the target that

$$\frac{\partial p_s(\vec{R})}{\partial n} + \frac{\partial p_i(\vec{R})}{\partial n} = 0,\ p_s(\vec{R}) = p_i(\vec{R}), \tag{3}$$

where $p_i(\vec{R})$ is the incident pressure including direct wave and reflection wave from the interface. In the case of unit point source, it has the same form with Greens function in Eq. (2).

For the far field and monostatic scattering, partial derivatives of Green's function and incident pressure can be expressed as

$$\frac{\partial G(\vec{r},\vec{R})}{\partial n} = \frac{\partial p_i(\vec{R})}{\partial n} = -jk\left[\frac{e^{jkr}}{r}cos\alpha + V(\theta)\frac{e^{jkr_1}}{r_1}cos\alpha_1\right], \tag{4}$$

where $cos\alpha = {}^{\partial r}/_{\partial n}$, $cos\alpha_1 = {}^{\partial r_1}/_{\partial n}$. Substituting Eqs. (3) and (4) into Eq. (1) yields

$$p_s = \frac{-jk}{2\pi}\int_S \left[\frac{e^{j2kr}}{r^2}cos\alpha + V\frac{e^{jk(r+r_1)}}{rr_1}(cos\alpha + cos\alpha_1) + V^2\frac{e^{j2kr_1}}{r_1^2}cos\alpha_1\right]dS. \tag{5}$$

These three integral terms in the Eq. (5) have distinct physical meanings: the first term and the third term are the monostatic scattering of the real source (path 1) and the image source (path 3), respectively; the second term represents the bistatic scattering between the real source and the image source (path 2).

As stated in Ref. [21–23], when meshing the target, the dimension of each element must satisfy the condition $R_{min} > D^2/\lambda$ guaranteeing the calculating field point being at far field, and R_{min} is the minimum distance of scattering point. D is the largest dimension of each element, and λ denotes the wavelength of the incident wave. Thus, the total scattered field is the superposition of the scattered fields of all elements. The integration in Eq. (5) on each element can be transformed into the sum of algebraic expressions with respect to the vertexes, that is

$$I_p = \int_{S_0} e^{2jk(ux+vy)}dxdy = \sum_{n=1}^{3}\frac{e^{-j2k(x_n u + y_n v)}(p_{n-1}-p_n)}{4k^2(u+p_{n-1}v)(u+p_n v)}, \tag{6}$$

where

$$p_n = \frac{y_{n+1}-y_n}{x_{n+1}-x_n},\ p_0 = \frac{y_1-y_3}{x_1-x_3}. \tag{7}$$

For Kirchhoff approximation on acoustic scattering of surface targets has not been verified in the published papers, a brief proof is given here. Monostatic scattering of the rigid semi-submerged sphere is derived. For convenience, the center of the sphere is coincident with the origin of spherical coordinate. The scattered pressure can be divided into two terms: the first term p_s' is monostatic scattering of the real source by the sphere in free field; the second term p_s'' is monostatic scattering of image source by the sphere in free field. For each term, acoustic scattering of the rigid sphere can be obtained via series expansion method after z-axis rotated to the direction of the real (image) source.

Due to symmetry, the incident and scattered waves have nothing to do with the azimuth. The unit incident spherical wave has the expansion [27]

$$p_i = jk\sum_{n=0}^{\infty}(2n+1)(-1)^n h_n^{(1)}(kr_0)j_n(kr)P_n(cos\theta), \tag{8}$$

and the scattering potential of the sphere is

$$p_s = j\sum_{n=0}^{\infty}A_n(2n+1)(-1)^n h_n^{(1)}(kr)P_n(cos\theta). \tag{9}$$

Insertion of the rigid boundary condition, it yields

$$A_n = -k\frac{h_n^{(1)}(kr_0)j_n'(ka)}{h_n^{(1)\prime}(ka)}. \tag{10}$$

The monostatic scattering of the rigid semi-submerged sphere is obtained

$$p_s = p_s' + p_s''. \tag{11}$$

The radius of the sphere is 1 m, the acoustic pressure at 1 m away from the point source is 1 Pa and the receiving point (the point acoustic source) is 10 m away from the center of sphere and 45° from horizontal plane as illustrated in Fig. 1.

Thus we obtain the echo strength (ES)

$$ES = 20\log|r_0^2 p_s/p_i| \tag{12}$$

Fig. 2(a) shows the comparison of ES between normal model solution and Kirchhoff approximation. Except for the low frequencies below

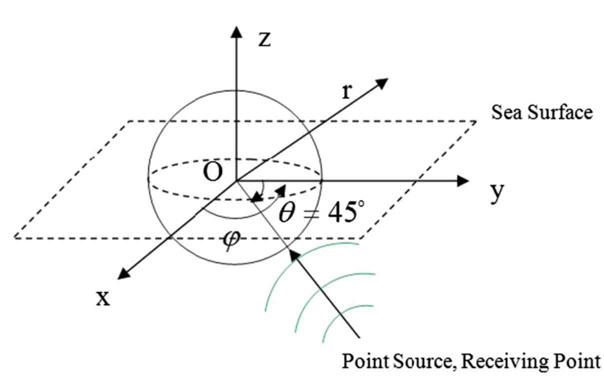

Fig. 1. Scattering of point source by a rigid semi-submerged sphere.